

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property
Organization
International Bureau



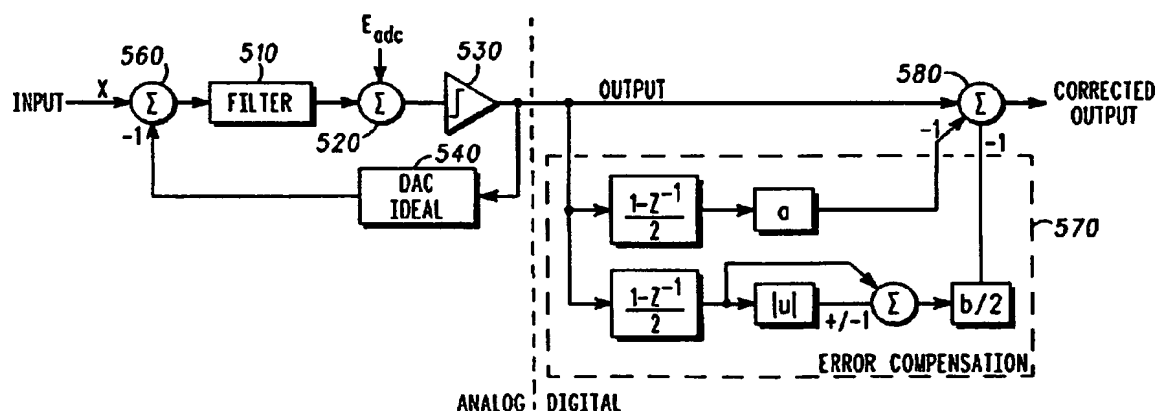
(43) International Publication Date
21 May 2004 (21.05.2004)

PCT

(10) International Publication Number
WO 2004/042932 A2

- (51) International Patent Classification⁷: **H03M 3/04**
- (21) International Application Number:
PCT/EP2003/050778
- (22) International Filing Date:
3 November 2003 (03.11.2003)
- (25) Filing Language: English
- (26) Publication Language: English
- (30) Priority Data:
02292758.6 6 November 2002 (06.11.2002) EP
- (71) Applicant (for all designated States except US): **MOTOROLA INC** [US/US]; 1303 E. Algonquin Road, Schaumburg, IL 60196 (US).
- (72) Inventors; and
(75) Inventors/Applicants (for US only): **IHS, Hassan** [FR/FR]; 8 rue Robert Aron, Apt 305, F-31100 Toulouse (FR). **BASTANI, Babak** [FR/FR]; 64 rue du Petit Train, F-31170 Tournefeuille (FR). **OUADDAH, Jalal** [FR/FR]; Résidence Canaletto, Apt 102, 5 allée du Niger, F-31000 Toulouse (FR).
- (81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.
- (84) Designated States (*regional*): ARIPO patent (BW, GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).
- Published:**
— without international search report and to be republished upon receipt of that report
- For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: CONVERTER, CIRCUIT AND METHOD FOR COMPENSATION OF NON-IDEALITIES IN CONTINUOUS TIME SIGMA DELTA CONVERTERS



(57) Abstract: A continuous time sigma delta converter has a filter (510) and converter components (530, 540) having known non-ideal characteristics. A compensation circuit (570) has error modelling components arranged to model the non-ideal characteristics of the converter. A summation block (490) combines a compensation signal from the compensation circuit (570) with a non-ideal output signal from the converter in order to provide a compensated output signal. This has substantially no effect on other modulator performance characteristics and contributes to the implementation of giga sample-per-second Continuous Time sigma deltas having the dynamic range capabilities of traditional DT sigma deltas.

BEST AVAILABLE COPY

WO 2004/042932 A2

- 1 -

CONVERTER, CIRCUIT AND METHOD FOR COMPENSATION OF NON-
IDEALITIES IN CONTINUOUS TIME SIGMA DELTA CONVERTERS

5 **Field of the Invention**

This invention relates to analogue-to-digital and digital-to-analogue converters, and particularly to such converters based on continuous time Sigma Delta
10 Modulation.

Background of the Invention

15 Continuous Time (CT) Sigma Delta Analogue-to-Digital and Digital-to-Analogue converters (ADCs), are considered the most appropriate type of ADC for high signal bandwidth applications. Indeed, CT sigma delta modulators have Factors Of Merit (FOM) from five to ten times better than
20 their Discrete Time (DT) counterparts, and even better when compared to other Nyquist rate ADCs. The FOM indicates the amount of power needed to convert an analogue signal to the least-significant-bit (LSB) of a digital signal and thus reflects the power consumption of
25 the converter for a given resolution (a given number of bits).

CT Sigma Delta modulators are of interest especially in the area of wireless communications, as they provide
30 potential alternatives to bulky and high power consuming switched capacitor Sigma Delta modulators used in both I (In-phase) and Q (Quadrature-phase) channels of radio

- 2 -

Intermediate Frequency (IF) sections. As recent 3rd generation (3G) wireless standards require higher IF signal bandwidth with little or no change in the signal Dynamic Range (DR), the power consumption will
5 dramatically increase if switched capacitor sigma deltas continue to be used in future 3G IF sections.

Although CT sigma deltas are the most power efficient ADCs, nevertheless, some of their non-idealities severely
10 limit their maximum achievable dynamic range. Two main non-idealities are the most limiting in CT sigma delta ADCs: (i) asymmetric rising and falling edges of the feedback path signal, and (ii) sampling clock jitter. These two problems, if addressed, would allow a CT sigma
15 delta ADC to be widely used in all aspects of low power, high signal bandwidth and high sampling frequency applications. The asymmetric rising and falling edges error may be referred to as Intersymbol Interference error. The harmonic distortions it introduces may be also
20 referred to as Intersymbol Distortions.

Referring firstly to FIG. 1, the general scheme of a known sigma delta modulator is constituted of a loop filter 10 (an integrator in general) of function H, an n-
25 bit ADC 30 and an n-bit DAC 40, a feedback summation block 60 and two error components associated with non-idealities: a first error component 20 of the forward path (E_{adc}) and a second error component 50 of the feedback path (E_{dac}). The filter 10 may be Discrete Time (DT) such
30 as a switched capacitor filter, or continuous time such as an active RC or Gm-C filter.

- 3 -

The modulator of FIG. 1 is characterized by the following equation that expresses the modulator's output Y as function of the input X , the function H of the filter 10 and the error components E_{adc} and E_{dac} :

5

$$Y = X \frac{H}{1+H} + E_{dac} \frac{H}{1+H} + E_{adc} \frac{1}{1+H} \quad (\text{Equation 1})$$

The function $\frac{H}{1+H}$ is a low-pass filter while $\frac{1}{1+H}$ is a high-pass filter. Thus, the non idealities of the forward path are high-pass filtered (noise-shaped) while the feedback path non-idealities are untouched and remain present in the signal baseband. Equation 1 shows clearly that the feedback path non-ideality errors E_{dac} are present in the signal baseband.

15

In multi-bit sigma deltas, the multi-bit feedback DAC suffers from non-linearity errors due to component mismatches. These errors show up as harmonics in the signal baseband in accordance with Equation 1. This is the main reason that single bit modulators are the most widely used in sigma delta ADCs since a one-bit feedback DAC is inherently linear.

Feedback path asymmetric rising/falling edges and sampling clock jitter are by far the most critical feedback path non-idealities in CT sigma deltas. These non-idealities do not significantly affect DT sigma deltas thanks to the sample and hold feature inherent in switched capacitor circuits. The errors related to clock jitter are not in fact created inside the feedback path,

30

- 4 -

but are rather produced by the circuitry that generates the clock. However the asymmetric rising/falling edges do originate from device mismatches in the feedback path. For the sake of simplicity, only single-bit sigma delta modulation is considered below. It will be understood that the following analysis for single-bit modulators can be extended to multi-bit modulators using well-known minor modifications.

10 The main sources of asymmetric rising/falling edges are mismatches between the path rising and falling time constants, the non-balanced or non-symmetric feedback DAC voltage thresholds, the non-symmetric spikes produced during signal transitions, etc.

15 Referring now to FIG. 2, there is shown a timing diagram which depicts an example of an ideal signal 70 and a real signal 80, both having a time period T_s . The real signal 80 has asymmetric rise/fall times 82 and 85 of t_m . This error gives rise to even order harmonics including a strong DC component and also gives rise to large Inter-modulation Distortions. It will be appreciated that even a small timing mismatch between rise and fall times can result in severe Signal to Noise and Distortion Ratio (SNDR) degradation.

From US patent number US5196853 there is known a robust technique that cancels distortion harmonics due to the asymmetric rising/falling edge mismatches. The technique, called Return to Zero (RZ), consists of returning to zero for half of each clock cycle the levels of a feedback DAC.

- 5 -

Referring now to FIG. 3 the RZ technique is shown. A non-RZ signal 90 exhibits usual behaviour, including an asymmetric rising/falling edge 95. An RZ signal 100
5 cancels distortion harmonics due to the asymmetric rising/falling edges mismatches. The RZ signal 100 returns to zero for half of each clock cycle, and for the other half of each clock cycle, it follows the levels of the feedback DAC 40 of FIG. 1.

10

This method is widely used in data communications where such a signal coding results in reduced Intersymbol Interferences. The RZ operation makes all the signal levels sensitive to non-ideal rising and falling edges,
15 in contrast to non-RZ (NRZ) operations where these non-idealities affect only signal levels that are adjacent to the transitions. In such a manner, the asymmetric transitions error appear as DC component error only, which is easily filtered with a digital high-pass filter
20 in a subsequent portion of the circuitry.

However, the RZ technique, although it efficiently cancels the Intersymbol Interferences, suffers from many side effects. In fact, with the RZ technique the signal
25 has now to settle and resolve in half a clock period. The settling process occurs at each clock cycle in contrast to the NRZ signals where it occurs only during signal transitions. The transition occurrence in RZ signals also occurs more often than in NRZ signals and leads to
30 increased occurrence of settling solicitation. This gives rise to the following issues:

- 6 -

1. The problem that RZ is supposed to resolve reappears in high sampling frequencies since full settling may not occur during the Return to Zero phase.
2. The jitter in-band power increases by 12dB (due the
- 5 halved signal level duration needed in the RZ technique).
3. The loop filter H needs to settle within half a clock period rather than one period in NRZ, leading to doubled current consumption.
4. RZ technique doubles transition occurrence, leading to
- 10 6dB increase in the power of transition spikes and errors.
5. RZ implementation requires additional circuitry that leads to additional current consumption and parasitics (e.g., switch charge injection, spikes).
- 15 6. The RZ technique does not compensate for a DC component; in fact, it shifts the power of the even order harmonics to DC.

A need therefore exists for compensation of feedback path

20 non-idealities of continuous time sigma delta ADCs wherein at least some of the abovementioned disadvantage(s) may be alleviated.

25 **Statement of Invention**

In accordance with a first aspect of the present invention there is provided a continuous time sigma delta converter as claimed in claim 1.

- 7 -

In accordance with a second aspect of the present invention there is provided a compensation circuit as claimed in claim 3.

- 5 In accordance with a third aspect of the present invention there is provided a method as claimed in claim 4.

- In accordance with a fourth aspect of the present
10 invention there is provided a method as claimed in claim 9.

- Preferably the summation block is arranged to subtract the compensation signal from the output signal in order
15 to provide the compensated output signal.

- The non-ideal characteristics are preferably associated with a feedback path of the converter. The non-ideal characteristics preferably include symmetrical errors
20 associated with non-ideal rising and falling edges of signal transitions of the converter.

- Preferably the non-ideal characteristics include asymmetrical errors associated with non-ideal rising and
25 falling edges of signal transitions of the converter. The compensation circuit preferably has calibration parameters determined by an dichotomy technique which iteratively refines the values of the calibration parameters.

30

- 8 -

Preferably the calibration algorithm uses a dichotomy technique which iteratively refines the values of the calibration parameters.

- 5 In this way a converter, circuit and method for compensation in continuous time sigma delta converters is provided which efficiently compensates for feedback path non-idealities. The compensation circuitry is totally digital facilitating straightforward integration and
10 minimizing related design effort. This has substantially no effect on other modulator performance characteristics and offers an alternative to commonly used compensation techniques that suffer from limiting side effects. It facilitates the implementation of giga sample-per-second
15 CT sigma deltas having the dynamic range capabilities of traditional DT sigma deltas.

Brief Description of the Drawings

20

One method and arrangement for compensation of feedback path non idealities of continuous time sigma delta ADCs incorporating the present invention will now be described, by way of example only, with reference to the
25 accompanying drawings, in which:

FIG. 1 shows a prior art sigma delta converter illustrating non-ideal characteristics;

30

FIG. 2 shows a prior art timing diagram of ideal and real rising and falling edge transitions of the converter of FIG. 1;

- 9 -

FIG. 3 shows a known prior art technique (Return to Zero) for providing compensation against the non-ideal transitions of the circuit of FIG. 1;

5

FIG. 4 shows an illustrative circuit diagram of a converter and a notional digital domain error model according to the invention;

10

FIG. 5 shows a composite timing diagram illustrating transition errors associated with the circuit of FIG. 4;

15

FIG. 6 shows an illustrative circuit diagram of a compensation circuit according to the invention;

20

FIG. 7 shows an illustrative circuit diagram of a converter having an ideal DAC and a notional error model, including the compensation circuit of FIG. 6;

FIG. 8 shows an illustrative circuit diagram of the converter and compensation circuit of FIG. 7 with a real DAC;

25

FIG. 9 shows an illustrative flow diagram of a dichotomy technique used to derive parameters for the compensation circuit of FIG. 6.; and

30

FIG. 10 shows an illustrative circuit diagram of a further compensation circuit according to the invention.

- 10 -

Description of Preferred Embodiment(s)

As can be seen from equation 1 above, feedback DAC
 5 related error E_{dac} is not noise-shaped and is transmitted
 in the same path as the input signal. If the same error
 signal can be reconstructed in the digital domain, it is
 possible to compensate for it by simply subtracting it
 from the output digital signal. The proposed method
 10 assumes that the error can be reconstructed in the
 digital domain using simple digital circuitry.

The principle is as follows: First, the error is
 reconstructed using digital circuitry that reproduces
 15 with a high degree of fidelity the analogue error E_{dac} .
 Second, this reconstructed digital error is subtracted
 from the digital PDM output signal before it passes
 through the decimation filter.

20 Referring now to FIG. 4, there is shown a circuit
 substantially similar to that of FIG. 1, having a loop
 filter 110 of function H , an ADC 130 and a DAC 140, a
 summation block 160 and error components 120 and 150.
 However, the circuit of FIG. 4 also includes an error
 25 compensation component 180, which represents the
 subtraction of E_{dac} .

The ADC transfer function for this subtraction is given
 by the following equation:

30

$$Y_c = X \frac{H}{1+H} - E_{dac} \frac{1}{1+H} + E_{adc} \frac{1}{1+H} \quad (\text{Equation 2})$$

- 11 -

Thus, unlike Equation 1 showing transfer function of a non compensated modulator, the DAC error E_{dac} is now noise-shaped the same way as the ADC error E_{adc} . It is
5 then removed from the signal baseband and its effect on the signal performances is no longer significant. Note that the error signal E_{dac} is analogue and complex. It is therefore difficult to reproduce it with a high degree of fidelity using only digital means. It will be shown below
10 that this is possible for errors resulting from asymmetric feedback path rising/falling edges using very simple circuitry.

To be able to reconstruct the signal error in the digital
15 domain, it is first necessary to build up a model that represents the error mechanism.

The loop filter H (filter 10 of FIG. 1) is generally a simple integrator, at least for the feedback path signal.
20 In practice, the modulator feedback path signal is subject to slewing due to parasitic time constants either on the feedback DAC or in the comparator or both. This gives rise to slow transitions that lead to an erroneous integrated signal at the output of the modulator's
25 integrator.

Referring now also to FIG. 5 there is shown a signal 200 having slow transitions and the equivalent error components at the output of the integrator H (box 230).
30 These components have been obtained by subtracting an integrated ideal signal 220 from an integrated real signal 210. Note that the signal integration corresponds

- 12 -

to the area delimited by the signal itself and the time axis.

Within the box 230 there are two types of integrated
5 signal error and these need to be modelled separately.
The first type of error is represented by the symmetrical
error areas 235, and this error is symmetric in the sense
that the rising and falling edges are substantially
equal. This type of error is referred to as a symmetric
10 integrated error. The second type of error is represented
by the asymmetrical error areas 245 and affects the
falling edge only (it may similarly affect the rising
edge only). It is referred to as asymmetric integrated
error.

15
Since the modulator's ADC (comparator in case of single
bit sigma delta) is active at clock rising edge only, the
shape of the integrator output signal before a clock
rising edge is of little interest as long as it converges
20 to the final (theoretical, ideal) value at that instant.

It is therefore possible to model transition related
errors with level equivalent error provided that they
have the same integration area. The signal experiencing
25 both errors (transition or level) will produce the same
integrator output voltage at the clock rising edge. Thus,
the error areas shown in box 230 may be equivalently
modelled by the level error areas shown in box 240. The
areas produce the same effects since their areas are
30 equal. Finally, the level equivalent error is shown in
waveform 250.

- 13 -

It is useful to normalize the transition integrated error areas 235 and 245 with respect to a unit level area $V_{dac} \cdot T_s$, where V_{dac} represents the signal level voltage. The normalized errors for both 235 (A) and 245 (B) are
 5 respectively:

$$a = \frac{A}{V_{dac} T_s}$$

$$b = \frac{B}{V_{dac} T_s} \quad \text{(Equation 3)}$$

10 Now that a level representation of the error is derived, it is possible to set a model that generates the transition errors of both A and B types. As the errors manifest themselves only when a transition occurs, a transition detector is needed in the model. A simple
 15 derivator may be used for that purpose but any other circuit that detects transitions can be used too.

Referring now also to FIG. 6, there is shown a circuit in which the whole model of the transition related errors is
 20 presented. Again the circuit is substantially similar to that of FIG. 1, having a loop filter 310 of function H, an ADC 330, a summation block 360 and error components 320 and 350. However, the circuit of FIG. 6 incorporates an ideal DAC 340 and an error modelling circuit 350 to be
 25 further described below.

To represent the level equivalent of the type A error (symmetric error), a derivator 370 of transfer function $\frac{1-z^{-1}}{2}$ is used within the modelling circuit 350 to detect

- 14 -

transitions, and an attenuation factor a (the normalized error A) that scales the derivator levels is provided by block 375. The derivator 370 generates a level of the same amplitude as the feedback path signal when a transition occurs. It returns and remains at zero when the signal is not in transition. For example, assuming that the DAC delay can be represented by a first order low pass filter time constant τ . The error area A is $A = \tau * V_{dac}$ and the parameter $a = \tau / T_s$.

10

Similarly the asymmetric transition error (error type B) is generated in the modelling circuit 350 using a derivator 380 whose output passes through two different paths. The first path is a simple wire which is coupled to a summation block 390, the second path contains the absolute value function $|u|$ (block 385), which is then fed to the summation block 390. The summation of both paths allows the negative part of the derivator output to be cancelled. This allows the injection of an error representing asymmetric error due to a slower rising edge. Alternatively, the subtraction of the second signal path from the first cancels the positive part of the derivator 380 output signal and thus models the asymmetric error due to a slower falling edge. An attenuation factor b (the normalized error B) is used to scale down the signal error in block 395. The absolute value function is a non linear functions that gives rise to even number harmonics only.

30 It has been shown above that the parameter b is critical to error compensation. The parameter a is 10 times less critical than b . It is not generally taken into account

- 15 -

except when its value is too high or when the modulator's OSR is low. When this parameter is too high, it may limit the maximum achievable peak SNDR by giving rise to third harmonics appearing only when the input signal is close
 5 to the full scale. When the OSR is low, it may increase the noise floor due to the leakage it introduces in the modulator Noise Transfer Function (NTF).

The errors that are due to feedback path symmetric and
 10 asymmetric transitions are respectively expressed in the following equations:

$$E_{dac}^a(z) = \frac{1-z^{-1}}{2} aY(z) \quad (\text{Equation 4})$$

$$15 \quad E_{dac}^b(z) = \left[\frac{1-z^{-1}}{2} Y(z) \mp \left| \frac{1-z^{-1}}{2} Y(z) \right| \right] \frac{b}{2} \quad (\text{Equation 5})$$

Now that a simple model is derived for the feedback path non-idealities error, it is now possible to reconstruct in the digital domain the same error and subtract it from
 20 the signal.

Referring now to FIG. 7 there is shown a digital compensation scheme using the modelling circuit of FIG. 6. The circuit of FIG. 7 is substantially similar to that
 25 of FIG. 6, having a loop filter 410 of function H, an ADC 430, an error component 420, an ideal DAC 440, a summation block 460 and an error modelling circuit 450. A second error modelling circuit 480, substantially identical to the error modelling circuit 450 is provided
 30 in the digital domain and its output is subtracted from

- 16 -

- the modulator's output. It is important that the parameters a and b implemented in the digital side match perfectly their analogue equivalent, otherwise the compensation will be leaky, similar to cascaded sigma
- 5 delta modulation where the digital compensation coefficients have to match their analogue counterparts. Below an algorithm is presented that determines the optimal parameters a and b.
- 10 The actual implementation of the compensation technique doesn't show the analogue model of the error since it is intrinsic to the feedback path. Referring now also to FIG. 8, there is shown an actual implementation using a real feedback DAC 540 in addition to a loop filter 510 of
- 15 function H, an ADC 530, an error component 520, a summation block 560 and an error modelling circuit 570 provided in the digital domain having its output is subtracted from the modulator's output.
- 20 All the functions used in the compensation paths are easily implemented in the digital domain including the absolute value function. As the modulator's output is a bit stream of 0s and 1s, one may ask how the compensation functions are applied on a single bit signal. In fact 0
- 25 and 1 in sigma delta represent respectively negative and positive full scale signals. Before going through the compensation circuitry they need first to be converted to full scale binary words. For instance, in an 8 bit signed binary word, 0 would be converted to "01111111" and 1
- 30 would be converted to "11111111".

- 17 -

The compensation scheme of FIG. 8 requires parameters a and b that represent the magnitude of the feedback non-ideality error to be experimentally measured. The direct measurement of these parameters is not straightforward
5 and typically involves the use of non-standard apparatus such as a Time Interval Analyzer. One easy way to measure their real values is to use a search algorithm that tries many arbitrary values picked using some informed means (dichotomy) and then selecting the optimal values.

10

To make this calibration procedure time effective, the compensation circuit needs to be duplicated in software mode so as to be able to run off-line (without soliciting the IC under calibration at each calibration process
15 cycle). The calibration procedure needs to be performed for each parameter separately.

The procedure works as follows:

- 1- One set of ADC (the device under calibration) output
20 samples is collected. These samples need to have been collected using a sine wave signal of full scale amplitude applied at the input of the ADC. Having collected this set of samples, the calibration procedure can now run off-line.
- 25 2- The SNDR of the collected data is calculated and the power of the harmonics extracted. If the SNDR meets the specification the calibration procedure stops, otherwise a coarse estimation P2 of the parameter under calibration is made based on the importance of the second harmonic.
- 30 3- The calibration algorithm starts using the estimated coarse value P2 as the initial value.

- 18 -

The calibration algorithm uses a dichotomy technique to refine the values of the parameter under calibration at each loop cycle. The starting point is the coarse segment [P1, P2] containing the parameter under calibration,

5 where, P1=0, P2 is the coarse value estimated in step 2 above. The program calculates the SNDR of the segment middle point $(P1+P2)/2$ and decides whether it needs to further refine the segment. If yes, two new segments are generated $[P1=P1 \ P2=(P1+P2)/2]$ and $[P1=(P1+P2)/2 \ P2=P2]$.

10 The SNDR of these two segments' middle points are calculated and the segment that contains the parameter under test is selected (the highest middle point SNDR). Two new segments are generated again and the same process is repeated until the SNDR goal is reached or after a

15 time-out period has elapsed.

Referring now to FIG. 9 there is shown a flow diagram of the calibration algorithm. At the start of the algorithm (box 600) P1=0 and P2= the coarse value. The first of two

20 calculation paths begins at block 610 where the calculation $P2=(P1+P2)/2$ is performed, and P1 is reset to the value of P1 in block 600. The second path begins at block 620 with the similar calculation $P1=(P1+P2)/2$ and P2 is reset to the value of P2 in block 600.

25 The results of block 610 are then used in the expression $SNDR_1(P1+(P1+P2)/4)$. Similarly the results of block 620 are used in the expression $SNDR_2(P2-(P1+P2)/4)$.

30 At block 660 the results of blocks 630 and 640 are compared: If $SNDR_1 > SNDR_2$ then the algorithm proceeds to

- 19 -

block 650; if not then the algorithm proceeds to block 670.

At block 650, SNDR_1 is compared to the specification. If
5 it passes the test, block 680 sets parameter
 $a(b) = P1 + (P1 + P2)/4$ and the program stops at block 685,
yielding the value of the parameter. If not the algorithm
proceeds to block 610, the value of $P2$ is refined
according to $P2 = (P1 + P2)/2$ and the loop is reiterated.

10

Similarly at block 670, SNDR_2 is compared to the
specification. If it passes the test, block 690 sets
parameter $a(b) = P2 - (P1 + P2)/4$ and the program stops at
block 695, yielding the value of the parameter. If not
15 the algorithm proceeds to block 620, the value of $P1$ is
refined according to $P1 = (P1 + P2)/2$ and the loop is
reiterated.

The program stops when either SNDR_1 or SNDR_2 passes the
20 spec, or when they do not vary for many loop cycles, or
when they start to decay after peaking. In the latter two
cases, the fault should not come from the feedback non-
ideality but from something else and the circuit under
calibration may be declared defective.

25

The number of cycles before convergence of this algorithm
depends on the starting point $P2$ and the SNDR required. A
starting Point $P2$ too far from the target and large SNDR
result in many algorithm cycles before convergence is
30 achieved. In all cases, no more than 10 cycles are
required to achieve convergence as the dichotomy
algorithm is the fastest one-dimension search algorithm.

- 20 -

Ten cycles of the algorithm is a matter of milliseconds of CPU time and consequently has no significant impact on the test time.

- 5 It will be readily appreciated that this technique may also be applied to Continuous Time Digital-to-Analog sigma delta modulation. Referring now also to FIG. 10, there is shown a sigma delta digital-to-analog conversion arrangement using a digital sigma delta modulator
- 10 comprising filter 710, ADC 730 and associated error E_{adc} 720 and a feedback path added to the input by summation block 760.

This digital arrangement is followed by an analog DAC 760

15 and a low pass filter 780. A DAC error E_{dac} 770 is also present. Similarly to the Analog-to-Digital sigma delta modulation, this error may be cancelled by reproducing it in the digital domain using the compensation circuit 740 and adding it to the sigma delta modulator feedback path

20 via summation block 750.

The DAC error is high pass-filtered in a similar manner to that of Equation 3 above. The same calibration algorithm as described above is also applicable.

25

It will be understood that the converter, circuit and method for compensation in continuous time sigma delta converters described above provides a technique that allows to efficiently compensate for feedback path non-

30 idealities. The compensation circuitry is totally digital facilitating straightforward integration and minimizing the related design effort. The technique does not

- 21 -

substantially affect other modulator performance characteristics and offers an alternative to commonly used compensation techniques that suffer from limiting side effects. Hence, it facilitates the implementation of
5 giga sample-per-second CT sigma deltas having the dynamic range capabilities of traditional DT sigma deltas.

The present invention does not directly deal with the effect of jitter, however the compensation it provides
10 for asymmetric rising/falling edges does not worsen the circuit jitter performance, in contrast to presently known techniques which do exactly that.

It will be appreciated that alternative embodiments to
15 those described above are possible. For example, the precise arrangement of circuit elements and portions of the calibration algorithm may differ from those described above.

20 Furthermore the arrangement and application of sigma-delta modulator may differ from the examples described above.

- 22 -

Claims

1. A continuous time sigma delta converter comprising:
conversion means (510, 520, 530, 540, 560) having known
5 non-ideal characteristics and arranged to provide an
output signal;
a compensation circuit (570) comprising error modelling
components (370, 375, 380, 385, 390, 395) arranged to
substantially model the non-ideal characteristics of the
10 conversion means (510, 520, 530, 540, 560); and
summation means (490) coupled to combine the compensation
signal with the output signal in order to provide a
compensated output signal.
- 15 2. The converter of claim 1 further characterised by:
the summation means (580) being arranged to subtract the
compensation signal from the output signal in order to
provide the compensated output signal.
- 20 3. A compensation circuit (570) for use with a
continuous time sigma delta converter (510, 530, 540,
560) having known non-ideal characteristics, the
compensation circuit (570) comprising error modelling
components (370, 375, 380, 385, 390, 395) arranged to
25 substantially model the non-ideal characteristics of the
converter (510, 530, 540, 560) in order to provide a
compensation signal,
wherein the compensation signal is combinable (580) with
a non-ideal output of the converter (510, 530, 540, 560)
30 in order to provide a compensated output signal.

- 23 -

4. A method for compensating for known non-ideal characteristics in a continuous time sigma delta converter (510, 530, 540, 560), the method comprising: converting an input signal of one time domain to an
5 output signal of another time domain using a converter (510, 530, 540, 560) having known non-ideal characteristics;
modelling the non-ideal characteristics of the converter in a compensation circuit (570);
10 combining a compensation signal output of the compensation circuit (570) with the output signal of the converter (510, 530, 540, 560) in order to provide a compensated output signal.
- 15 5. The converter of claim 1 or claim 2, circuit of claim 3 or method of claim 4 further characterised by: the non-ideal characteristics being associated with a feedback path (540) of the converter.
- 20 6. The converter, circuit or method of any preceding claim further characterised by: the non-ideal characteristics including symmetrical errors (235) associated with non-ideal rising and falling edges (230) of signal transitions of the converter (510, 530, 540,
25 560).
7. The converter, circuit or method of any preceding claim further characterised by: the non-ideal characteristics including asymmetrical (245) errors
30 associated with non-ideal rising and falling edges (230) of signal transitions of the converter (510, 530, 540, 560).

- 24 -

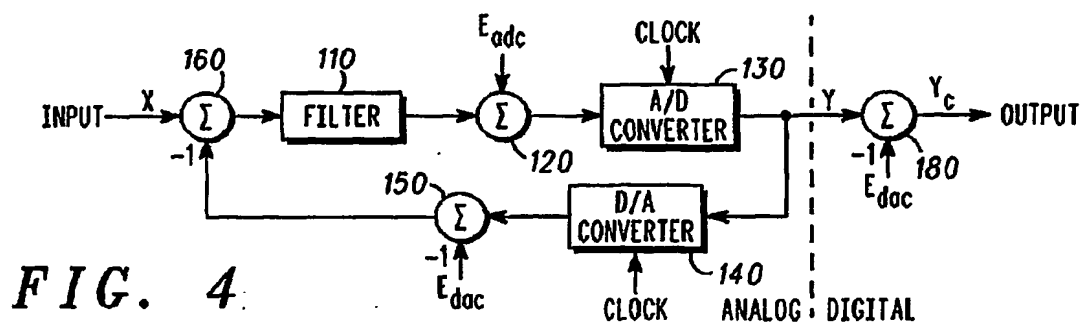
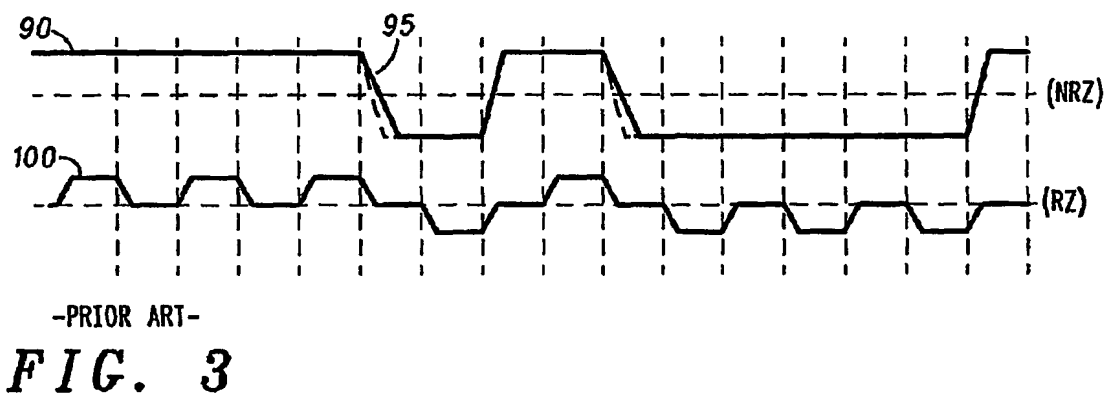
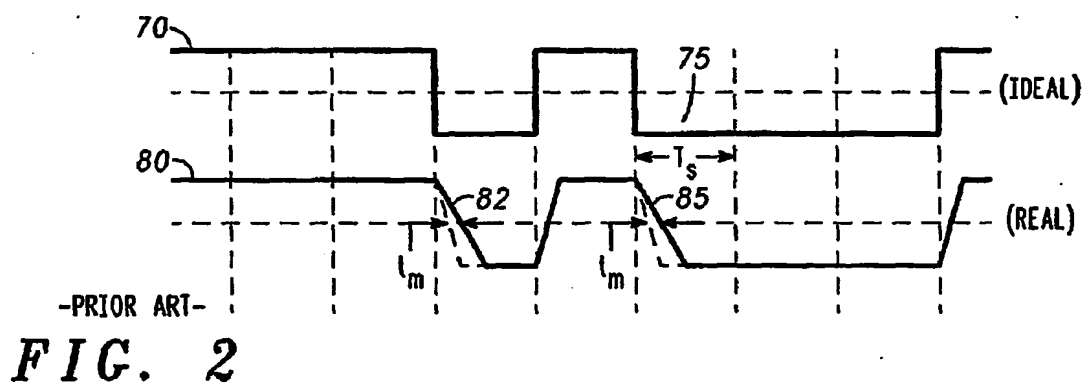
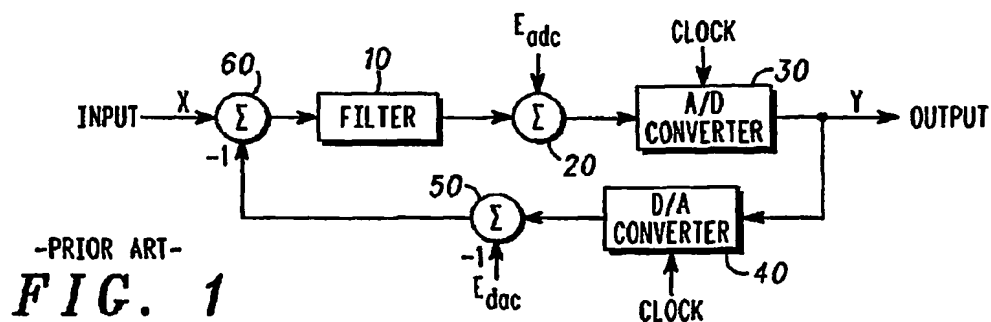
8. The converter, circuit or method of any preceding claim further characterised by: the compensation circuit (570) having calibration parameters (375, 395) determined
5 by an dichotomy technique which iteratively refines the values of the calibration parameters (375, 395).

9. A method for producing calibration parameters for use in the compensation circuit (570) of any preceding
10 claim, the method comprising the steps of:
collecting output samples from the converter (510, 530, 540, 560);
calculating a Signal to Noise and Distortion Ratio of the collected data;
15 determining whether the calculated Signal to Noise and Distortion Ratio meets specified performance criteria;
selectively recalculating the Signal to Noise and Distortion Ratio in dependence upon the step of determining, using a calibration algorithm (600-695).

20

10. The method of claim 9 wherein the calibration algorithm uses a dichotomy technique (600-695) which iteratively refines the values of the calibration parameters.

25



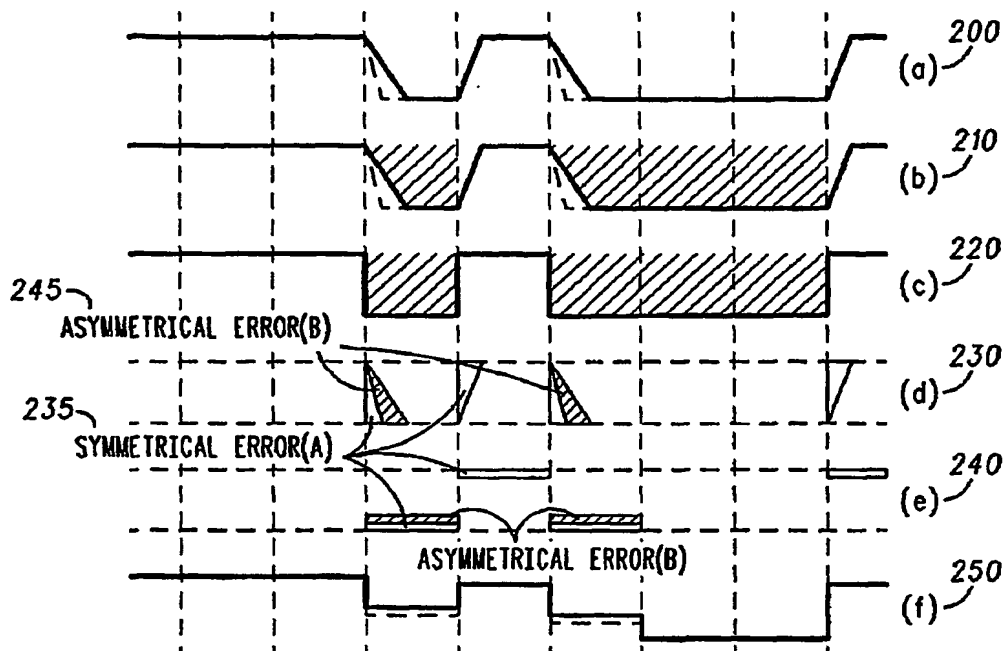


FIG. 5

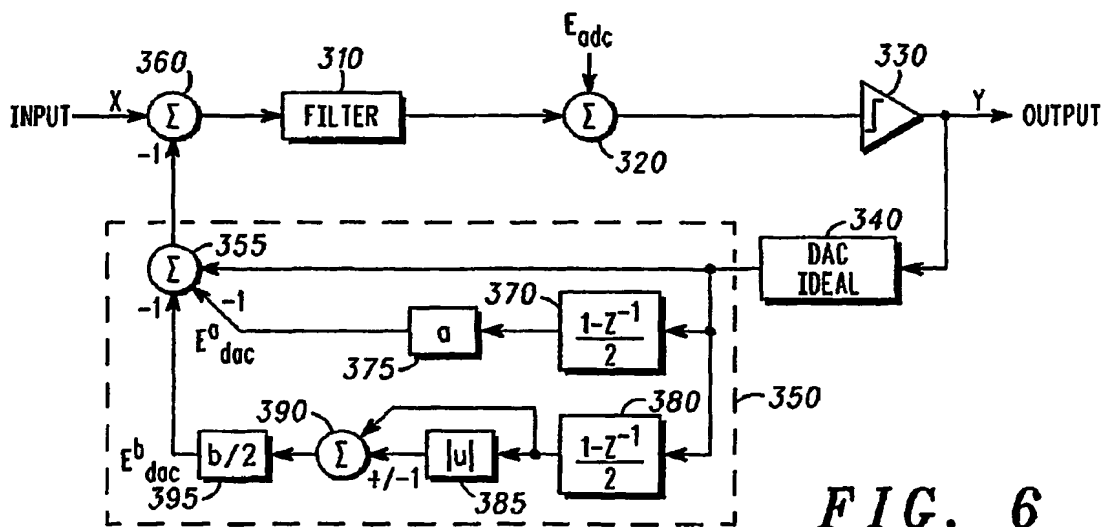


FIG. 6

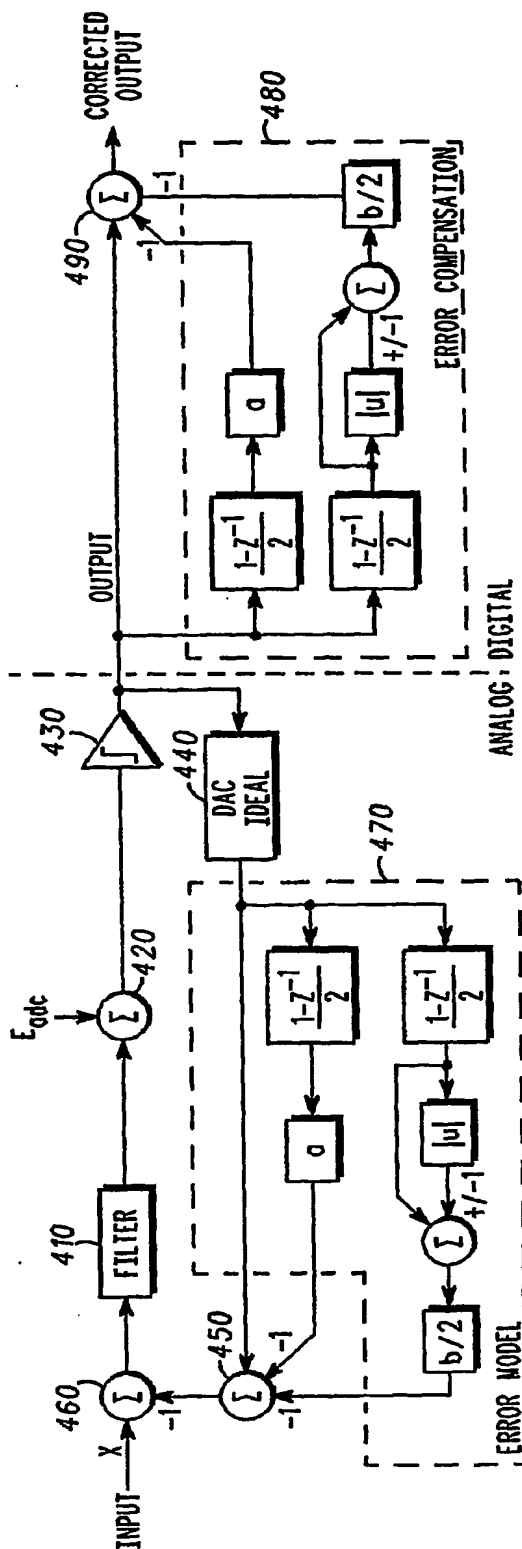


FIG. 7

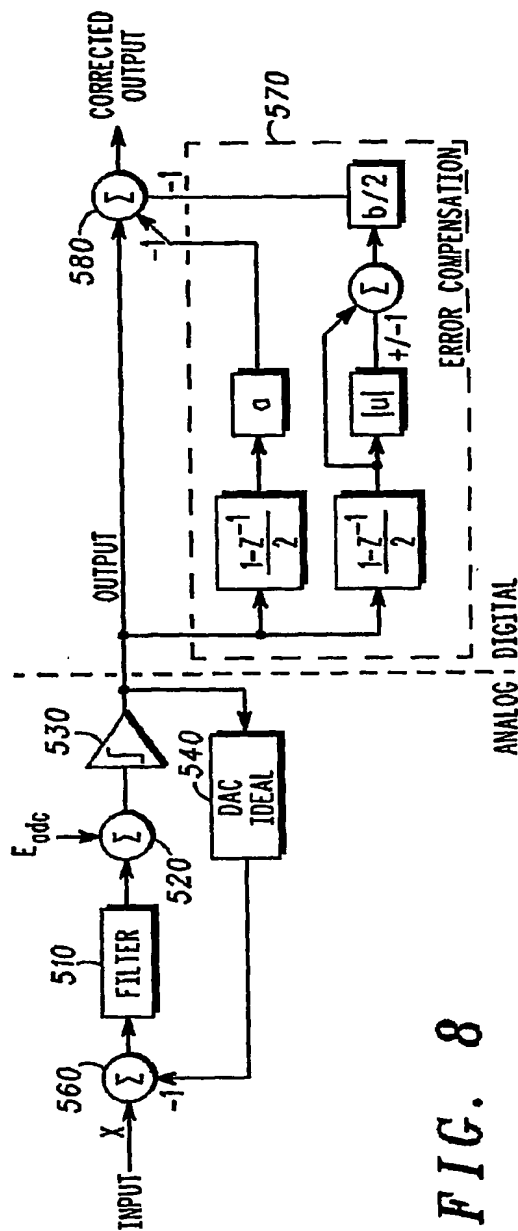


FIG. 8

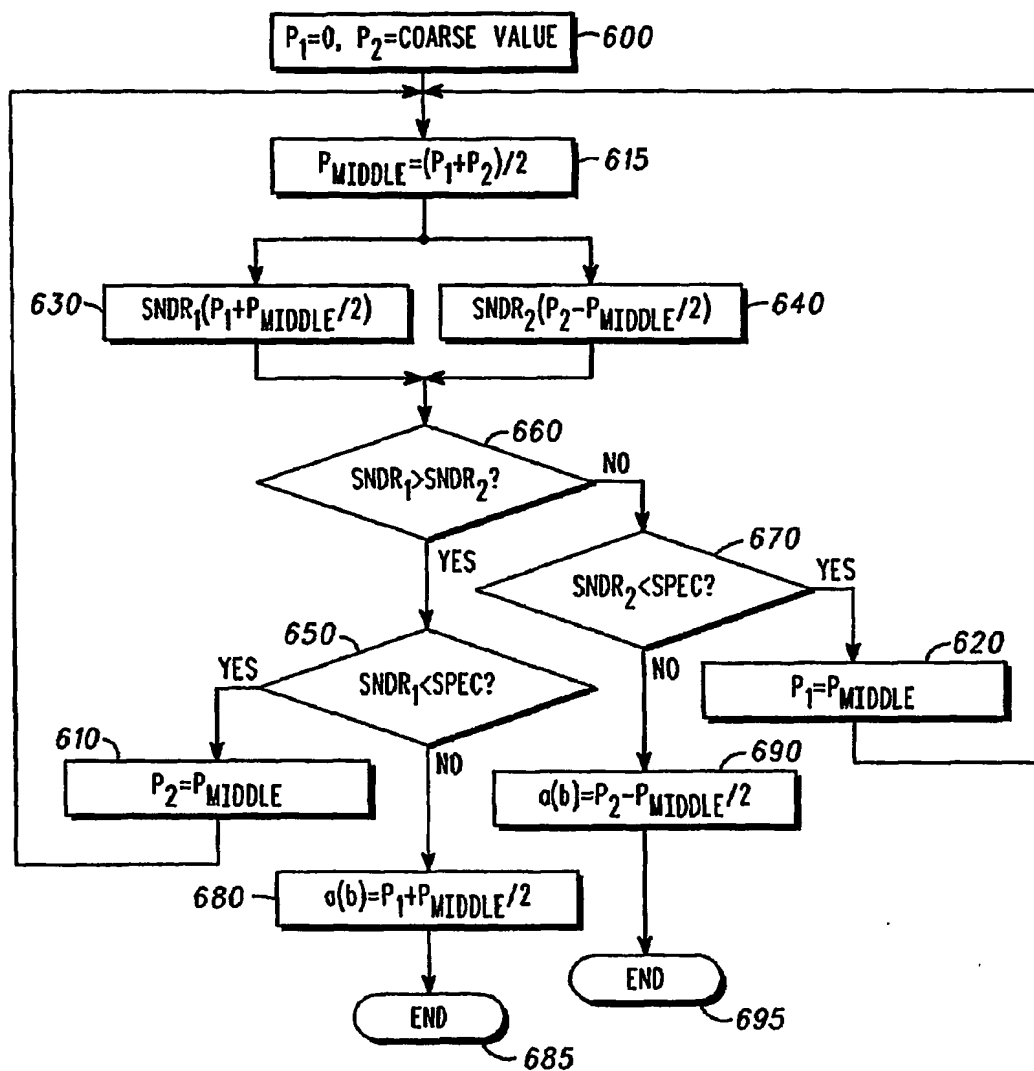


FIG. 9



WO 2004/042932 05 MAY 2005

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property
Organization
International Bureau



(43) International Publication Date
21 May 2004 (21.05.2004)

PCT

(10) International Publication Number
WO 2004/042932 A3

(51) International Patent Classification⁷: H03M 3/00

(21) International Application Number:
PCT/EP2003/050778

(22) International Filing Date:
3 November 2003 (03.11.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
02292758.6 6 November 2002 (06.11.2002) EP

(71) Applicant (for all designated States except US): MO-
TOROLA INC [US/US]; 1303 E. Algonquin Road,
Schaumburg, IL 60196 (US).

(72) Inventors; and

(75) Inventors/Applicants (for US only): IHS, Hassan
[FR/FR]; 8 rue Robert Aron, Apt 305, F-31100 Toulouse
(FR). BASTANI, Babak [FR/FR]; 64 rue du Petit Train,
F-31170 Tournefeuille (FR). OUADDAH, Jalal [FR/FR];
Résidence Canaletto, Apt 102, 5 allée du Niger, F-31000
Toulouse (FR).

(74) Agent: McCORMACK, Derek, J.; Motorola European
Intellectual Property Operations, Midpoint, Alencon Link,
Basingstoke, Hampshire RG21 7PL (GB).

(81) Designated States (national): AE, AG, AL, AM, AT, AU,
AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU,
CZ, DE, DK, DM, DZ, EC, EE, EG, ES, FI, GB, GD, GE,
GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR,
KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK,
MN, MW, MX, MZ, NI, NO, NZ, OM, PG, PH, PL, PT,
RO, RU, SC, SD, SE, SG, SK, SL, SY, TJ, TM, TN, TR,
TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

(84) Designated States (regional): ARIPO patent (BW, GH,
GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW),
Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM),
European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE,
ES, FI, FR, GB, GR, HU, IE, IT, LU, MC, NL, PT, RO, SE,
SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA,
GN, GQ, GW, ML, MR, NE, SN, TD, TG).

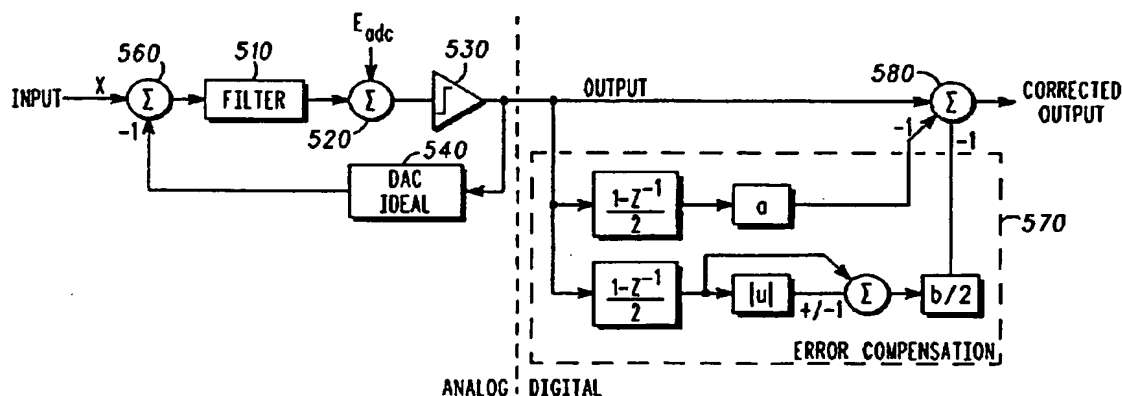
Published:

— with international search report
— before the expiration of the time limit for amending the
claims and to be republished in the event of receipt of
amendments

(88) Date of publication of the international search report:
26 August 2004

For two-letter codes and other abbreviations, refer to the "Guid-
ance Notes on Codes and Abbreviations" appearing at the begin-
ning of each regular issue of the PCT Gazette.

(54) Title: CONVERTER, CIRCUIT AND METHOD FOR COMPENSATION OF NON-IDEALITIES IN CONTINUOUS TIME
SIGMA DELTA CONVERTERS



(57) Abstract: A continuous time sigma delta converter has a filter (510) and converter components (530, 540) having known non-ideal characteristics. A compensation circuit (570) has error modelling components arranged to model the non-ideal characteristics of the converter. A summation block (490) combines a compensation signal from the compensation circuit (570) with a non-ideal output signal from the converter in order to provide a compensated output signal. This has substantially no effect on other modulator performance characteristics and contributes to the implementation of giga sample-per-second Continuous Time sigma deltas having the dynamic range capabilities of traditional DT sigma deltas.

WO 2004/042932 A3

INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 03/50778

A. CLASSIFICATION OF SUBJECT MATTER

IPC 7 H03M3/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 7 H03M

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the International search (name of data base and, where practical, search terms used)

EPO-Internal, WPI Data, INSPEC, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2001/038350 A1 (PAILLARDET FREDERIC ET AL) 8 November 2001 (2001-11-08) abstract; figure 5 paragraph '0016! - paragraph '0017! paragraph '0021! paragraph '0046! paragraph '0047! claim 1	1-5,8-10
A	US 6 016 112 A (KNUDSEN NIELS) 18 January 2000 (2000-01-18)	

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

A document defining the general state of the art which is not considered to be of particular relevance

E earlier document but published on or after the international filing date

L document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

O document referring to an oral disclosure, use, exhibition or other means

P document published prior to the international filing date but later than the priority date claimed

T later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

X document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

Y document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

Z document member of the same patent family

Date of the actual completion of the international search

7 June 2004

Date of mailing of the international search report

17/06/2004

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040, Tx. 31 651 epo nl,
Fax: (+31-70) 340-3016

Authorized officer

Oliveira, J.

INTERNATIONAL SEARCH REPORT

International Application No
PCT/EP 03/50778

Patent document cited in search report		Publication date		Patent family member(s)		Publication date
US 2001038350	A1	08-11-2001	FR	2805940 A1		07-09-2001
			EP	1137190 A1		26-09-2001
			US	2003021024 A1		30-01-2003
US 6016112	A	18-01-2000	US	5781137 A		14-07-1998
			US	5781138 A		14-07-1998
			US	6020838 A		01-02-2000
			US	6049298 A		11-04-2000

**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☒ BLACK BORDERS
- ☐ IMAGE CUT OFF AT TOP, BOTTOM OR SIDES
- ☐ FADED TEXT OR DRAWING
- ☒ BLURRED OR ILLEGIBLE TEXT OR DRAWING
- ☐ SKEWED/SLANTED IMAGES
- ☐ COLOR OR BLACK AND WHITE PHOTOGRAPHS
- ☐ GRAY SCALE DOCUMENTS
- ☐ LINES OR MARKS ON ORIGINAL DOCUMENT
- ☐ REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY
- ☐ OTHER: _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.